Year: 2019

Effect of different loading pistons on stress distribution of a CAD/CAM silica-based ceramic: CAD-FEA modeling and fatigue survival analysis

Miranda, Jean Soares ; de Carvalho, Ronaldo Luís Almeida ; de Carvalho, Rodrigo Furtado ; Borges, Alexandre Luis S ; Bottino, Marco Antônio ; Özcan, Mutlu ; de Melo, Renata Marques ; Souza, Rodrigo Othávio de Assunção e

Abstract: Purpose: This study evaluated the effect of different loading pistons, made of various materials and with different elastic moduli acting as antagonist material, on stress distribution and fatigue behavior of a CAD/CAM silica-based ceramic. Materials and methods: Discs of CAD/CAM made silica-based ceramic (N = 60) (VITA MARK II) were divided into six groups (n = 10 per group), according to the test method (M: Monotonic; F: Fatigue) and the antagonist piston material (T: Tungsten; S: Steel; G: Epoxy resin). FT, FS and FG combinations were submitted to mechanical cycling (2×10 cycles, 4 Hz, 45 N). The bending stress after fatigue were also valuated using Weibull analysis and the parameters (eta), (beta) and the mean time to failure (MTTF) were calculated. Fractographic analysis and Finite Element Analysis (FEA) were performed. Data were analyzed using ANOVA and Tukey's tests (alpha=0.05). Results: MG presented significantly less bending strength (MPa) (75.6) compared to MT (87.8) and MS (84.4) ($p < 0.05$). Six specimens from FT (MMTF: 8.3×10 ; :0.60; :5.6×10), four from FS (MMTF: 1.9×10 ; :1.2; :2.0×10) and one from FG (MMTF: 1.3×10 ; :0.48; :0.64×10) survived the fatigue test. The stress peak on the tensile surface of S was similar to that of T and both were less than that of G. The failure origins were on the tensile surface. Conclusion: The epoxy resin pistons were able to decrease the bending stress, and life expectancy (faster failure) of a silica-based ceramic compared to tungsten and steel.

DOI: https://doi.org/10.1016/j.jmbbm.2019.03.011

CAM silica-based ceramic: CAD-FEA modeling and fatigue survival analysis. Journal of the Mechanical Behavior of Biomedical Materials, 94:207-212.
DOI: https://doi.org/10.1016/j.jmbbm.2019.03.011

Effect of different loading pistons on stress distribution of a CAD/CAM silica-based ceramic: CAD-FEA modeling and fatigue survival analysis

Jean S Miranda[a], Ronaldo Luís A de Carvalho[a], Rodrigo F de Carvalho[b], Alexandre Luis S Borges[a], Marco Antônio Bottino[a], Mutlu Özcan[c], Renata MM Marinho[a*] Rodrigo Othávio de A e Souza[d*]

[a]Institute of Science and Technology, Univ Estadual Paulista – Unesp, São José dos Campos. São Paulo, Brazil

[b]Federal University of Juiz de Fora (UFJF), School of Dentistry, Minas Gerais, Brazil

[c]University of Zürich, Dental Materials Unit, Center for Dental and Oral Medicine, Clinic for Fixed and Removable Prosthodontics and Dental Materials Science, Zurich, Switzerland

[d]Federal University of Rio Grande do Norte (UFRN), Department of Dentistry, Division of Prosthodontics, Natal, Rio Grande do Norte, Brazil

Short title: *Effect of different loading pistons on stress distribution on silica ceramic.*

***Corresponding author at:** Rodrigo Othávio de Assunção e Souza

UFRN - Federal University of Rio Grande do Norte, Health Science Center, Department of Dentistry. Avenida Senador Salgado Filho, nº 1787. Natal/RN – Brazil - 59056-000.

E-mail: rodrigoothavio@gmail.com.

Phone number: +55 (84) 32154104

ABSTRACT

Purpose: This study evaluated the effect of different loading pistons, made of various materials and with different elastic moduli acting as antagonist material, on stress distribution and fatigue behavior of a CAD/CAM silica-based ceramic.

Materials and Methods: Discs of CAD/CAM made silica-based ceramic (N=60) (VITA MARK II) were divided into six groups (n=10 per group), according to the test method (M: Monotonic; F: Fatigue) and the antagonist piston material (T: Tungsten; S: Steel; G: Epoxy resin). FT, FS and FG combinations were submitted to mechanical cycling ($2x10^6$ cycles, 4Hz, 45 N). The bending stress after fatigue were also valuated using Weibull analysis and the parameters η (eta), β (beta) and the mean time to failure (MTTF) were calculated. Fractographic analysis and Finite Element Analysis (FEA) were performed. Data were analyzed using ANOVA and Tukey`s tests (alpha=0.05).

Results: MG presented significantly less bending strength (MPa) (75.6) compared to MT (87.8) and MS (84.4) ($p<0.05$). Six specimens from FT (MMTF: $8.3x10^6$; β:0.60; η:5.6 $x10^6$), four from FS (MMTF: $1.9x10^6$; β:1.2; η:2.0x 10^6) and one from FG (MMTF: $1.3x10^6$; β:0.48; η:$0.64x10^6$) survived the fatigue test. The stress peak on the tensile surface of S was similar to that of T and both were less than that of G. The failure origins were on the tensile surface.

Conclusion: The epoxy resin pistons were able to decrease the bending stress, and life expectancy (faster failure) of a silica-based ceramic compared to tungsten and steel.

Keywords: Biaxial flexural strength; bending stress; fatigue; feldspar ceramic; finite element analysis; stress; survival

1. Introduction

The last two decades have witnessed the development of new ceramics for dental reconstructions capable of embracing greater loads and surviving longer under masticatory function (Qasim, 2007; Oilo et al., 2014). Currently, computer-aided design/computer-aided manufacturing (CAD/CAM) using ceramic block milling system allows for (Qasim, 2007; Lin et al., 2012) fabrication of prefabricated ceramic blocks with improved mechanical properties owing to the standard process of fabrication and thereby obtaining more homogeneous material (Aurélio et al., 2015; Figueiredo-Pina et al., 2016). In order to ensure favorable mechanical behavior and to estimate clinical performance, materials are initially evaluated under laboratory conditions (Kelly, 1999; Basso et al., 2016; Homai et al., 2016). Among many test methods, the most widely used one is flexural strength test that estimates the strength of the material through a simple monotonic bending test (Kelly et al., 2010; Matinlinna, 2014). Unfortunately, monotonic tests do not truly simulate the stress involved in most clinical failures (Kelly et al., 2010). A more reliable and clinically relevant prediction of the strength and survival of a material can be obtained through cyclic fatigue analysis (Kelly, 1999; Bonfante et al., 2015; Ramos et al., 2015; Aboushelib and Elsafi, 2016; Basso et al., 2016). Exposing materials to fatigue conditions is essential for the prediction of the long-term performance of dental materials prior to clinical use (Silva et al., 2010; Abousheilib and Elsafi, 2016).

Laboratory tests used for ceramics generate stresses and modes of failures that differ from those observed clinically (Kelly et al., 2010) since the behavior of a ceramic material is very susceptible to the testing conditions (Yang et al., 2014), such as thickness and geometry of the specimen (Kelly, 1999; Oilo et al., 2014; Ramos et al., 2015; Basso et al., 2016), type of loading piston (Qasim, 2007), frequency of the load application (Borba et al., 2013), humidity (Kelly et al., 2010), and type of piston movement (Basso et al., 2016; Qasim et al., 2006). Therefore, all these factors should be analyzed preclinically for a more faithful simulation of ceramic behavior in the clinic.

The simulation of the opposing tooth or restoration acting forces upon ceramics could be simulated using pistons made of different materials that influences the maximum stress distributed throughout the specimen

(Bhowmick et al., 2007; Qasim, 2007; Kelly et al., 2010). Traditionally, the piston is made of tungsten but in limited number of studies piston materials were changed to steel, epoxy resin, or wood (Qasim, 2007; Kelly et al., 2010. On the other hand, Finite Element Analysis (FEA) of low modulus piston materials loaded against ceramic substrates showed a tendency for higher fracture loads on feldspathic porcelain that was validated by a single-load to failure mechanical test (Weber et al., 2018). Therefore, more information is needed on the effect of poston materials and their possible effects of survival of ceramic materials.

The objectives of the present study were to a) verify the mechanical behavior of a CAD/CAM silica-based ceramic when subjected to monotonic loading and cyclic fatigue test performed using pistons made of different materials (tungsten, steel, epoxy resn) and b) to determine the stress distribution in the ceramic specimens as a function of the piston material using FEA. The null hypotheses tested were that 1) the survival of the ceramic would not be affected with the three piston materials, and 2) that there would be no difference in the results of biaxial flexural strength among the groups.

2. Material and methods

2.1 Ceramic and piston specimen fabrication

Feldspar CAD/CAM ceramic blocks (VITA MARK II, Vita Zahnfabrik, Bad Säckingen, Germany) were cut to standard dimensions (diameter: 12 mm; thickness: 1.2 mm) (N=60) by means of a diamond cutting disc (Extec High Concentration, Enfield, CT, EUA) at low speed and under water irrigation (IsoMet 1000 Precision Saw, Buehler, Plymouth, Minessota, EUA). Subsequently, both sides of each disc were standardized using silicon carbide paper in sequence (#400, #600, and #1200 grit) (Norton Saint Gobain) under water irrigation in a polishing machine (EcoMet 250 Grinder Polisher, Buehler). The discs were then randomly divided into six groups (n=10, per group), according to the test method (M: Monotonic; F: Fatigue) and the antagonist piston material (T: Tungsten; S: Steel; G: Epoxy resin) yielding to groups identified as MT, MS, MG, FT, FS, and FG.

Ten pistons, with a diameter of 1.6 mm and a length of 2 mm, were made of T, S and G (Fig. 1) and fixed to the metal base by a metal base that ensured their retention.

2.2 Biaxial bending test

One piston from each group was chosen randomly for the biaxial bending test. Discs from the MT, MS, and FM groups were used for this test. The flexural strength was determined in a Universal Testing Machine (EMIC DL-1000, EMIC Sao Jose dos Pinhais, Brazil) and testest were performed according to ISO 6872: 2015. The dimensions of each ceramic disc were measured with a digital caliper (model 500-195-20B, Mitutoyo, Mitutoyo Ltda,Tokyo, Japan) prior to the test. The center of each specimen was loaded (load cell: 100 Kgf) at a crosshead speed of 1 mm/min until fracture. All specimens were tested in distilled water.

2.3 Fatigue survival test

Specimens from the FT, FS and FG groups were subjected to the mechanical cycling test in a fatigue simulation device (CICLA 10, Erios Equipamentos, São Paulo, Brazil) with ten chambers that allowed ten specimens to be cycled simultaneously under the same conditions in water for a duration of $2x10_6$ cycles at a frequency of 4 Hz and a constant load of 45 N.

The discs were then placed on metal holders (Ø=39.5 mm; height: 15 mm) where on the upper surface, each device had three balls (Ø=3.2 mm) fixed equidistantly 10 mm distant to the center, forming a circular plane with a diameter of 10 mm. In order to guide the positioning of the specimen on the metallic balls and to prevent the specimens from moving during cycling loading, three metal stems (Ø=2 mm; height: 4 mm) were fixed at a distance of 17 mm to the center, so that the center of the plane formed by the balls coincided with the center of the metal stems (Souza et al., 2013). Throughout the cycling process, the pistons were in contact with the central part of the upper surface of each sample (compression side), inducing loading/unloading cycles. The number of cycles before disc failure was recorded.

2.4 Finite Element Analysis (FEA)

One specimen was modeled with CAD software (Rhinoceros 4.0, McNeel North America, Seattle, USA), exported in an *.stp* file to CAE software (version 16.0; Ansys) (Fig. 2). A static structural analysis was applied according to the fatigue experimental set-up. The parameters used were: 45 N loading where all contacts were considered to have a frictional coefficient of 0.25; all materials were considered isotropic, linear, and homogeneous for the static structural analysis; and mesh applied until 1% convergence was achieved (44.969 tetrahedral and hexahedral elements and 105.756 nodes), with the mathematic error lower than 1%. The Young´s modulus and Poisson´s Ratio for each material are displayed in Table 1.

2.5 Fractographic analysis

In order to determine the failure origins, the fracture marks and damage modes, fractography analysis was performed. All failed specimens from each group were first inspected by optical stereomicroscopy (Stereo Discovery. V12; Carl Zeiss, Göttingen, Germany), and then one representative disc from each group was chosen for scanning electron microscope (SEM) analysis (FEI, Phillips, Brno, Czech Republic). For SEM analysis, the selected specimens were cleaned with 70% alcohol (Alves Santa Cruz Ltda., Guarulhos, SP, Brazil), dried, and coated with a thin layer (12 nm) of gold (EMITECH SC7620, East Sussex, United Kingdom).

2.6 Statistical analysis

Data of biaxial bending test were analyzed using a statistical software package (IBM SPSS Software V.23, Chicago, IL, USA). Kolmogorov-Smirnov and Shapiro-Wilk tests were used to test normal distribution of the data. ANOVA and the Tukey`s tests were used to identify the significant diffrences between the groups. P values less than 0.05 were considered to be statistically significant in all tests.

At the end of $2x10_6$ cycles, the surviving discs were censored in the Weibull analysis. The scale parameter η (eta), the shape parameter β (beta) and mean time to failure (MTTF) for a 90% confidence interval were obtained using a software (Weibull ++ 9, Reliasoft.inc, Michigan, USA), with a bilateral 95% confidence interval. The maximum likelihood method was used as the method of analysis and the Fisher Matrix method for calculation of the confidence limits. The η parameter determined the time interval between "t_0" and "t", in which 63.2% of failures occured.

3. Results

3.1 Monotonic and fatigue survival tests

Biaxial flexural test and MTTF results indicated significantly less load required to fracture the specimen when the epoxy resin (G) was used as a piston material used compared to those of T and S ($p<0.001$) (Table 2).

In the fatigue test, the sopecimens in the FT group showed a higher survival rate, with 6 specimens surviving the cyclic fatigue condiditons ($\beta=0.60$), followed by 4 specimens in the FS group ($\beta=1.19$). The FG group completed the $2x10^6$ cycles with the highest incidence of failures, with nine specimens fracturing during the test ($\beta=0.48$) (Table 3).

The η values for the groups cycled with T, S, and G piston materials were 5.5 $x10^6$, $2.04x10^6$, and $0.64x10^6$, respectively. Probabilities of failure results are presented in Figs. 3a-c.

3.2 FEA results

The piston materials showed similar stress distribution, mainly on the tensile surface of the disc. Stress peaks (MPa) caused by S (42.06) and T(41.60) pistons were similar but higher for the G (44.99) piston material (Figs. 4a-f).

3.3 Fractography analysis

SEM micrographs (x100) indicated the failure origin on the tensile surfaces of the monotonic test specimens, showing similar patterns of fracture (Figs. 5a-f). On the compression surface, however, the defect caused by the piston tip was present, being less prominent in the specimens tested with G. In the FG specimens, the fractured surfaces were smoother than in FS and FT groups.

4. Discussion

This study intended to evaluae the stress distribution and the mechanical behavior of a CAD/CAM silica-based ceramic when subjected to the mechanical test performed using various piston materials with different elastic moduli. In contrast to previous studies, where focus was mainly on different piston shapes and load application at different points for the analysis of failure propagation in glasses or ceramics (Qasim et al., 2005; Qasim et al., 2006; Qasim et al., 2007; Weber et al., 2018), this study aimed to define how the materials of such pistons influence stress distribution and how this would affect the fatigue strength of a CAD/CAM feldspar ceramic.

In vivo, it has been estimated that masticatory forces vary between 12 and 70 N (Rosentritt et al., 2009). Based on that and according to more current resuls repored (Ramos et al., 2015), the load chosen in the survival test was 45 N, at a frequency of 4 Hz for a number of 2×10^6 cycles, approximating a number of cycles corresponding to four years of clinical funcion (Aboushelib and Elsefi, 2016). In addition, aging was performed in distilled water in order to simulate the moisture in the oral cavity (Zhang et al., 2010; Borba et al., 2013), which is useful for reliability analyses (Kelly et al., 2010; Silva et al., 2011) as humid environment leads to the propagation of small cracks within the ceramic, thus facilitating crack growth (Yang et al., 2014).

Regarding the sensitivity of the fatigue tests as a function of the piston material, it is known that the elastic modulus of the constituting material affects the failure mode of the specimens (Kelly et al., 2010). An inox (stainless) steel piston has a high elastic modulus and creates Hertzian failures on the surface that is not compatible with clinical findings while epoxy resin was found not to damage the compression surfaces of the specimens that were exposed to fatigue. However, through tests with a ceramic structure bonded to an alumina base and a polycarbonate substrate fatigued with tungsten and glass pistons, Bhowmick et al. (2007) have suggested that the failure of the ceramic was only slightly sensitive to the material constituting the indenter. The results observed from the survival test in this study differed from those of Bhowmick et al. (2007), leading to the rejection of the first null hypothesis, since the number of specimens that survived until completion of the 2×10^6 cycles varied in the experimental groups. Our results were also in contrast to those of Weber et al. (2018) who found an increase in the failure load of ceramics with a resin piston. This was probably due to the use of multilayered specimens and taking only load to failure of the ceramics into consideration.

Considering that a the masticatory cycle in a dentate young adult (22-32 years old) lasts approximately one second (Lepley et al., 2010), the mean time to failure (life expectancy) of all three groups in years, would correspond to more than 50 years. The beta values lower than 1 in the FG and FS groups denote a tendency for early failures of the ceramic when fatigued with those piston materials. However, the first inspection was performed only after 500.000 cycles since no failures were observed before that. Therefore, although we cannot precisely state the exact failure moment, a considerable amount of cycles passed until fracture of the first specimens.

Fractography analysis indicated that the defects originating from the tensile surface varied in shape and size, although the CAD/CAM blocks are theoretically considered to be structurally more homogeneous compared to hand-made ones (Aurélio et al., 2015). Therefore, the two softer materials showed a tendency to accelerate a critical defect growth on the ceramic (Silva et al., 2011), while the material with the highest modulus caused mainly Hertzian cone cracks on the compression surface. In this case, most likely there was a competition between failure modes and therefore more fatigue cycles were required until the fracture occurred. SEM images also showed similar failure patterns for all groups whereas fatigue-fractured surfaces were smoother than those subjected to monotonic loading, due to the speed of crack propagation (Homaei et al., 2016). In the monotonically loaded specomens on the other hand, defects in the compression surface were visible caused by the fast and heavy load, unlike the fatigued groups, where the load was subcritical and constant.

The monotonic test results reinforced the observations from the survival test since the epoxy resin group (FG) required a lower load to fracture the feldspathic ceramic discs than did the FS and FT groups, leading to the rejection of the second null hypothesis, that there would be no differences in biaxial flexural strength among the groups. In this regard, FEA method was used to help clarify the results of monotonic test which clearly showed the effect of the elasticity modulus of the piston material on the failure probability of the feldspathic ceramic disc. It has been also previously observed that less rigid materials such as epoxy resin, distribute tension stress more evenly (Kelly et al., 2010). In this case, tensile stress was evenly distributed, reaching the tensile surface of the disc and weakening the ceramic with a lower load, in a smaller time interval, causing fracture. This led to the rejection of the hypothesis that the stress distributions observed in the FEA would be similar independent of the piston material. It has to be noted that during both fatigue survival and the monotonic biaxial bending tests, the pistons neither required replacement nor suffered from deformation which is not I,n agreement with an earlier study (Bhowmick et al. 2007b) where glass piston was used to perform the fatigue tests.

When metal pistons with a high elastic modulus are used in preclinical tests, there may be an overestimation of the resistance of the ceramic, failing to reflect its actual clinical behavior (Kelly, 1999; Yang et al., 2014). The epoxy resin used in the pistons showed results suggesting a more homogeneous stress distribution on the feldspathic ceramic disc. Therefore, even within some limitations, such as no further analysis of the antagonist pistons after the mechanical tests, not bonding the ceramic specimens on dentin and not replicating the anatomical complexity of the cusps (Qasim et al., 2005; Qasim, 2008; Ramos et al., 2015), the results of this study could be considered highly relevant for the mechanical analysis of ceramics in laboratory tests.

5. Conclusions

From this study, the following could be concluded:

1. Pistons made of different materials led to differences in the bending strength, fatigue behavior and stress distribution on the tested CAD/CAM feldspar ceramic.
2. The epoxy resin piston was able to generate a more homogeneous stress distribution in the ceramic specimens, reaching the tensile surface more evenly and resulting failures in a shorter period, when compared with the tungsten and steel piston materials.

Clinical Relevance

Stress distribution and thereby fatigue behaviour of feldspar ceramic material is affected by the antagonist material type exerting force on the material where epoxy resin created more homogeneous stress distribution but less life expectancy. Clinical observations of feldspar ceramic tested should report on the antagonist material to verify these findings.

Acknowledgements

The authors gratefully acknowledge the Institute of Science and Technology of UNESP São José dos Campos for allowing the execution of this methodology in its laboratories.

Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

References

Aboushelib MN, Elsafi MH. 2016. Survival of resin infiltrated ceramics under influence of fatigue. Dent Mater 2016;32:529-534.

Aurélio IL, Fraga S, Dorneles LS, Bottino MA, May LG. Extended glaze firing improves flexural strength of a glass ceramic. Dent Mater 2015;31:316-324.

Basso GR, Moraes RR, Borba M, Duan Y, Griggs JA, Della Bona A. Reliability and failure behavior of CAD-on fixed partial dentures. Dent Mater 2016;32:624-630.

Bhowmick S, Meléndez-Martínez JJ, Hermann I, Zhang Y, Lawn BR. Role of indenter material and size in veneer failure of brittle layer structures. J Biomed Mater Res B Appl Biomater 2007;82:253-259.

Bhowmick S, Meléndez-Martínez JJ, Zhang Y, Lawn BR. Design maps for failure of all-ceramic layer structures in concentrated cyclic loading. Acta Mater 2007;7:2479-2488.

Bonfante EA, Suzuki M, Lorenzoni FC, Sena LA, Hirata R, Bonfante G., et al. Probability of survival of implant-supported metal ceramic and CAD/CAM resin nanoceramic crowns. Dent Mater 2015;31:168-177.

Borba M, Cesar PF, Griggs JA, Della Bona AStep-stress analysis for predicting dental ceramic reliability. Dent Mater 2013;29:913-918.

Figueiredo-Pina CG, Patas N, Canhoto J, Cláudio R, Olhero SM, Serro AP, et al. Tribological behaviour of unveneered and veneered lithium disilicate dental material. J Mech Behav Biomed Mater 2016;53:226-238.

Homaei E, Farhangdoost K, Tsoi JK, Matinlinna JP, Pow EH. Static and fatigue mechanical behavior of three dental CAD/CAM ceramics. J Mech Behav Biomed Mater 2016;59:304-313.

Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. J Prosthet Dent 1999;81:652-661.

Kelly JR, Rungruanganunt P, Hunter B, Vailati F. Development of a clinically validated bulk failure test for ceramic crowns. J Prosthet Dent 2010;104:228-238.

Lepley C, Throckmorton G, Parker S, Buschang PH. Masticatory performance and chewing cycle kinematics-are they related? Angle Orthod 2010;80:295-301.

Lin WS, Ercoli C, Feng C, Morton D. The effect of core material, veneering porcelain, and fabrication technique on the biaxial flexural strength and Weibull analysis of selected dental ceramics. J Prosthodont 2012;21:353-362.

Matinlinna, J.P., 2014. Handbook of Oral Biomaterials. 1st ed. Singapore: Pan Stanford Publishing Pte Ltd. 156-70.

Oilo, M., Kvam, K., Gjerdet, N.R., 2014. Simulation of clinical fractures for three different all-ceramic crowns. Eur J Oral Sci. 122, 245-250.

Qasim T, Bush MB, Hu X, Lawn BR. Contact damage in brittle coating layers: influence of surface curvature. J Biomed Mater Res B Appl Biomater 2005;73:179-185.

Qasim T, Ford C, Bush MB, Hu X, Lawn BR. Effect of off-axis concentrated loading on failure of curved brittle layer structures. J Biomed Mater Res B Appl Biomater 2006;76:334-339.

Qasim T. Influences of complex loading and margin geometry: failure of curved brittle layer structures. Int J Fracture. 2007;144:35-44.

Qasim T, Ford C, Bush MB, Hu X, Malament KA, Lawn BR. Margin failures in brittle dome structures: relevance to failure of dental crowns. J Biomed Mater Res B Appl Biomater 2007;80:78-85.

Ramos GF, Monteiro EB, Bottino MA, Zhang Y, Marques de Melo R. Failure probability of three designs of zirconia crowns. Int J Periodont Rest Dent 2015;35:843-849.

Rosentritt M, Behr M, van der Zel JM, Feilzer AJ. Approach for valuating the influence of laboratory simulation. Dent Mater 2009;25:348-352.

Silva NR, Bonfante EA, Zavanelli RA, Thompson VP, Ferencz JL, Coelho PG. Reliability of metalloceramic and zirconia-based ceramic crowns. J Dent Res 2010;89:1051-1056.

Silva NR, Bonfante EA, Rafferty BT, Zavanelli RA, Rekow, ED, Thompson VP, et alModified Y-TZP core design improves all-ceramic crown reliability. J Dent Res 2011;90:104-108.

Souza RO, Valandro LF, Melo RM, Machado JP, Bottino MA, Özcan M. Air-particle abrasion on zirconia ceramic using different protocols: effects on biaxial flexural strength after cyclic loading, phase transformation and surface topography. J Mech Behav Biomed Mater 2013;26:155-163.

Weber KR, Benetti P, Della Bona Á, Corazza PH, Medeiros JA, Lodi E, Borba M. How does the piston material affect the in vitro mechanical behavior of dental ceramics? J Prosthet Dent 2018;120:747-754.

Yang R, Arola D, Han Z, Zhang X. A comparison of the fracture resistance of three machinable ceramics after thermal and mechanical fatigue. J Prosthet Dent 2014;112:878-885.

Zhang L, Wang Z, Chen J, Zhou W, Zhang S. Probabilistic fatigue analysis of all-ceramic crowns based on the finite element method. J Biomech 2010;43:2321-2326.

Captions to tables and figures:

Tables:

Table 1. Material type, its respective Young's modulus, Poisson's ratio and source references.

Table 2. Results of the biaxial flexural strength test (Mean±SD) and MTTF of experimental groups. SD: standard deviation; MTTF: Mean time to failure; MPa: Mega pascal. The same superscript letters in one column show no significant difference.

Table 3. Number of specimens failed every $5x10_5$ cycles in each experimental group.

Figures:

Fig. 1 Pistons made of different materials **a)** tungsten, **b)** epoxy resin, **c)** stainless steel to apply tension in the center of the fedlspar ceramic specimens.

Figs. 2a-b Photos of **a)** the rendered model (spheres, disk and piston) exported in *.stp* file to CAE software Ansys, **b)** geometries meshed with tetrahedral and hexahedral elements.

Figs. 3a-c Failure probability x time (number of cycles) plot for the **a)** FT, **b)** FS and **c)** FG groups. The blue line represents the failure probability of the respective group with a 95% level of bilateral confidence. Red lines indicate the confidence interval. Note that the FS group specimens needed notably longer time until failure while most of the FG specimens damaged after a short time under fatigue conditions.

Figs. 4a-f Digital models of the discs showing the Maximum Principal Stress distribution at the center and magnified tensile surface to 3 groups: **a-b)** tungsten piston, **c-d)** stainless steel, **e-f)** epoxy resin. Note that under the same loading, the energy reached the tensile surface with higher stress concentration in the epoxy resin group.

Figs. 5a-f Fractography analysis of the ceamic surfaces under SEM (x100) from he groups **a)** MT, **b)** MS, **c)** MG, **d)** FT, **e)** FS, **f)** FG. Note that the cracks propagated from the tensile zone under tension (cc: cone crack; hl: hackles; o: failure origin).

Tables:

Table 1. Material type, its respective Young's modulus, Poisson's ratio and source references.

Material	Young´s modulus [GPa]	Poisson´s Ratio	References
Tungsten (T)	400	0.28	Sonelastic
Stainless steel (S)	200	0.3	Ansys Library
Epoxy resin (G)	14.9	0.3	Kelly et al., 2010
Vita Mark II	64	0.25	Yang et al., 2014

	N	Mean±SD (MPa)		MTTF (cycles)	Upper Bound (cycles)	Lower Bound (cycles)
MT	10	87.8±6.7^{A}	**FT**	8.287086x10^{6}	5.449812x10^{7}	1.260150x10^{6}
MS	10	84.4±3.0^{A}	**FS**	1.923478x10^{6}	3.419032xx10^{6}	1.082110x10^{6}
MG	10	75.6±5.1^{B}	**FG**	1.354818x10^{6}	4.207733x10^{6}	436228.357181

Table 2. Results of the biaxial flexural strength test (Mean±SD) and MTTF of experimental groups. SD: standard deviation; MTTF: Mean time to failure; MPa: Mega pascal. The same superscript letters in one column show no significant difference.

Cycles	FT	FS	FG
1 - $5x10^5$	2	2	5
$5x10^5$ - $1x10^6$	2	1	-
$1x10^6$ - $1.5x10^6$	-	3	2
$1.5 x10^6$ - $2x10^6$	-	-	2

Table 3. Number of specimens failed every $5x10^5$ cycles in each experimental group.

Figures:

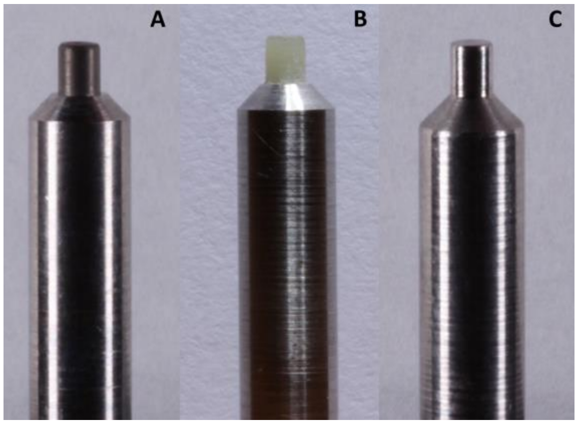
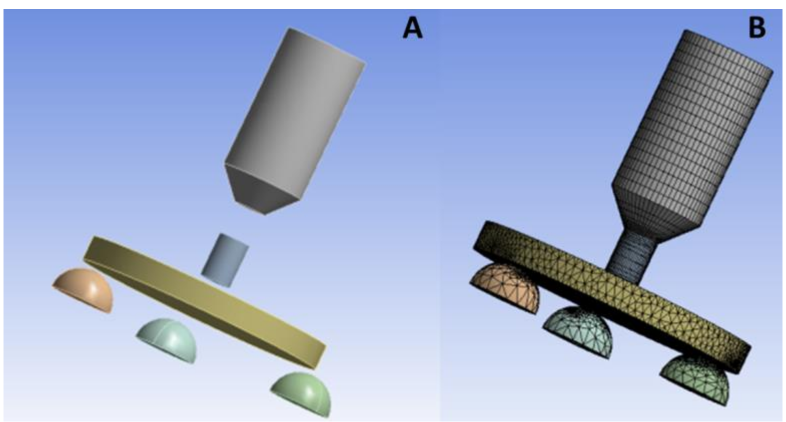
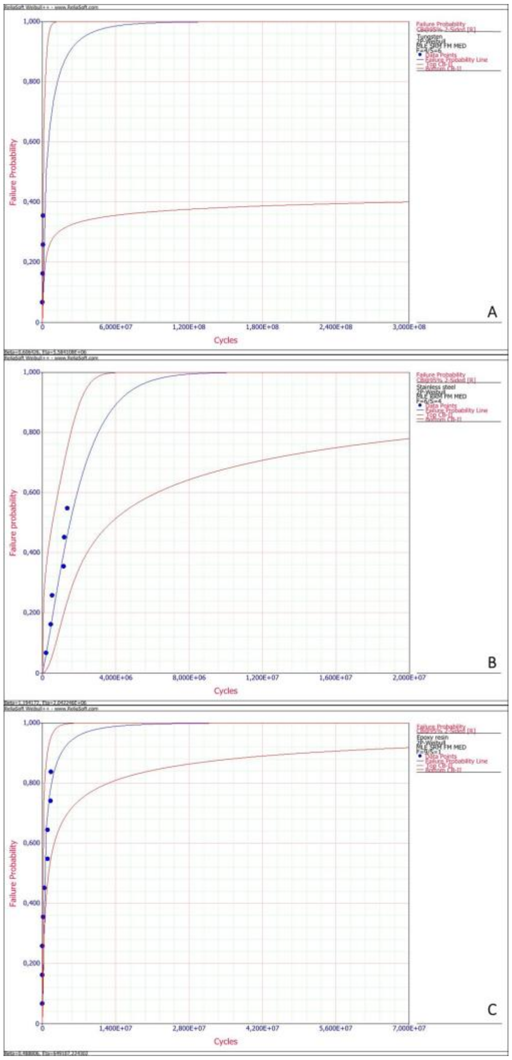


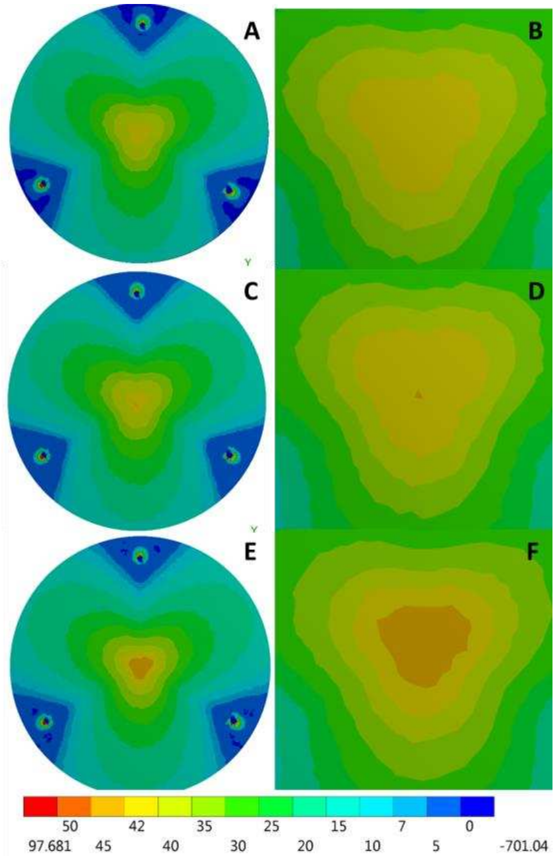
Fig. 1 Pistons made of different materials **a)** tungsten, **b)** epoxy resin, **c)** stainless steel to apply tension in the center of the fedlspar ceramic specimens.



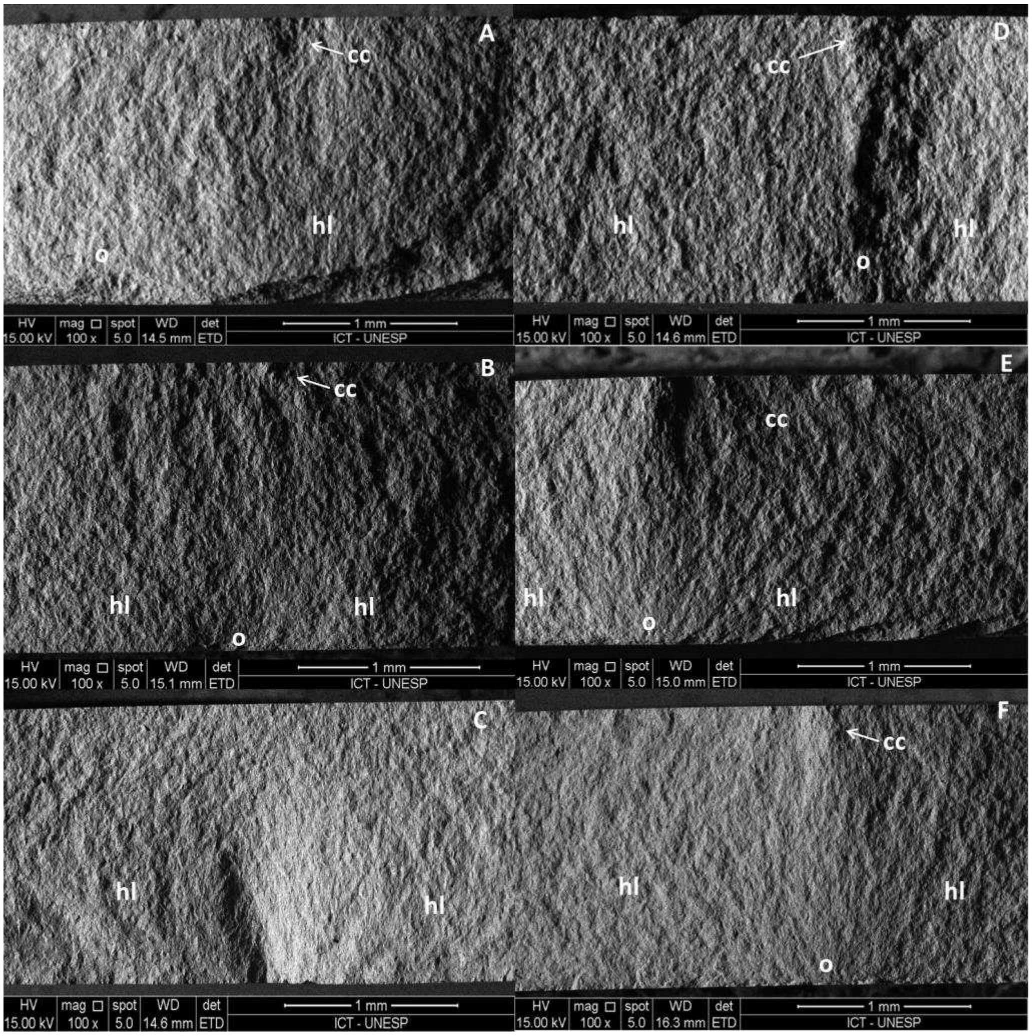
Figs. 2a-b Photos of **a)** the rendered model (spheres, disk and piston) exported in *.stp* file to CAE software Ansys, **b)** geometries meshed with tetrahedral and hexahedral elements.



Figs. 3a-c Failure probability x time (number of cycles) plot for the **a)** FT, **b)** FS and **c)** FG groups. The blue line represents the failure probability of the respective group with a 95% level of bilateral confidence. Red lines indicate the confidence interval. Note that the FS group specimens needed notably longer time until failure while most of the FG specimens damaged after a short time under fatigue conditions.



Figs. 4a-f Digital models of the discs showing the Maximum Principal Stress distribution at the center and magnified tensile surface to 3 groups: **a-b)** tungsten piston, **c-d)** stainless steel, **e-f)** epoxy resin. Note that under the same loading, the energy reached the tensile surface with higher stress concentration in the epoxy resin group.



Figs. 5a-f Fractography analysis of the ceamic surfaces under SEM (x100) from he groups **a)** MT, **b)** MS, **c)** MG, **d)** FT, **e)** FS, **f)** FG. Note that the cracks propagated from the tensile zone under tension (cc: cone crack; hl: hackles; o: failure origin).